

Final Technical Report

Project Title:

High Rate Laser Pitting Technique for Solar Cell Texturing

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1. Executive Summary

Efficiency of crystalline silicon solar cells can be improved by creating a texture on the surface to increase optical absorption. Different techniques have been developed for texturing, with the current state-of-the-art (SOA) being wet chemical etching. The process has poor optical performance, produces surfaces that are difficult to passivate or contact and is relatively expensive due to the use of hazardous chemicals.

This project investigated the feasibility of using high rate laser pitting as an alternative process for texturing mc-Si. Expected benefits for this new approach compared to the current SOA texturing process include:

- Superior optical surfaces for reduced front-surface reflection and enhanced optical absorption in thin mc-Si substrates that result in up to 0.5% absolute efficiency gain
- Improved surface passivation
- More easily integrated into advanced back-contact cell concepts
- Reduced use of hazardous chemicals and waste treatment
- Similar or lower cost

The project comprised laser process development for high-rate pitting, development of advanced optical systems for beam splitting and manipulation and the characterization of laser textured wafers. Main project goals of the program included the demonstration of pitting rates up to 400mm²/s, the development of special beam splitting optic for multi-spot processing and the development of system concepts to scale up the process for commercial use.

In-depth process development and parameter optimization was performed to optimize the material removal and to minimize the required energy to create a single pit with a depth of 10µm. Using a tunable MOPA fiber laser that provided 20W at the work piece a maximum pitting rate of 360mm²/s was demonstrated. With the advancement in laser technology, more powerful industrial laser systems (>50W) are available today that will allow to significantly exceed the target rate of 400mm²/s. Different optical concepts for splitting a single collimated beam into multiple beams. Maintaining the beam quality and creating an even power distribution between the individual beams were main considerations. The selected approach is based on a mirror that exhibits sections of different reflectivity. A prototype optic that creates 5 individual beams was designed, built and successfully tested. Wafers were textured and characterized with regard to surface reflectivity. The evaluation revealed that subsequent wafer etching must be further optimized and tailored to the laser textured surface to optimize surface reflectivity.

The demonstration of high-rate laser pitting feasibility using a single beam and the proof of concept for a beam splitting optic lay the groundwork to develop concepts for process scale-up. Different scenarios were assessed that enable processing of an entire 6" wafer with a single, high power laser source or multiple lower power sources at cycle times that are expected to be competitive to conventional texturing methods.

The performed research with the goal to maximize process efficiency is of high value for many aspects of silicon processing. The study clearly shows that using a tunable solid state laser allowing to control important processing parameters independently over a wide range is an ideal tool to determine optimum conditions for material removal. Knowledge of these conditions for silicon does not only result in best possible processing rates for laser pitting, as investigated here, but will also benefits other laser operations in solar cell manufacturing such as the drilling of via holes for more advanced cell design using EWT- or MWT-technology. Advanced and highly efficient

processing techniques can enable gains in solar cell efficiency and also reduces manufacturing costs and therefore supports the solar industry to stay competitive in the market.

2. Comparison of Accomplishments with Project Goals

The goals and objectives of the program focused on the proof of concept in 3 main areas:

- Demonstrate feasibility of achieving pitting rate of $400\text{mm}^2/\text{s}$ with a single beam using max. laser power of 30W
- Develop and demonstrate prototype optical system for beam splitting and processing with multiple spots
- Develop concept for scaling up process to meet production requirements

With the available laser system a maximum pitting rate of $360\text{mm}^2/\text{s}$ was demonstrated, which is only 10% below the target. This rate was obtained with 20W average laser power at the work piece and a 80mm focal length. The pulse energy is $50\mu\text{J}$ pulse energy at a pulse width of 283ns. The limiting factor was the maximum scanning velocity of 8m/s. Galvanometric scanners can move the beam very fast, but in order to reach a small spot size, a short focal length must be used and this sets limits for the maximum scanning velocity. In this case the scanning velocity was limited to 8,000mm/s.

In comparison, using the 163mm focusing optic was used, the process was not limited by the scanning rate, but by the laser power. Best experiments resulted in a pitting rate of $322\text{mm}^2/\text{s}$ using 20W of laser power. Availability of 25W on work piece would be sufficient to reach the milestone of $400\text{mm}^2/\text{s}$. Due to continued advancement in industrial pulsed laser sources through the course of this development program, increased output power in excess of 25W is available today. Therefore reaching and even exceeding the milestone is feasible.

The prototype optical system for beam splitting was successfully developed and tested. It consists of 2 two mirrors, one having sections that are partially reflective. The demonstrator optic met well the project goals and is capable of

- Creating 5 focal spots from a single collimated beam
- Maintaining beam quality during beam splitting
- Distributing power fairly evenly between the five beams

Further vendor qualification will help to improve the performance of the partially reflective mirror. The first prototype had slight deviation from the specifications for the reflectivity in each section. In addition, some engineering efforts are needed to transfer the prototype into a rugged production device.

The goal of the project was $400\text{mm}^2/\text{s}$ processed area using a single beam. For a single wafer of $156 \times 156\text{mm}^2$ and a cycle time of 7.2sec this means that using five beam optics the theoretical area covered by a single beam should be $>676\text{mm}^2/\text{s}$. Based on the achieved results the requirements for production equipment capable of doing the laser texturing entire wafers ($156 \times 156\text{mm}^2$) can be calculated. The energy to do a $10\mu\text{m}$ pit using an approximate $20\mu\text{m}$ focal spot size was $50\mu\text{J}$ and the energy required to do a pit with $40\mu\text{m}$ spot size was approximately $200\mu\text{J}$. It can therefore be concluded that the fluence (J/mm^2) of the pulse is similar in both cases; doubling the spot diameter by two creates a four time larger spot area and also the energy required to create the pit was four times higher. Therefore, these two known parameters can be used to estimate optimal parameters for pitting.

The limitation with the 20 μm spot size was the scanner movement and for 40 μm spot size the laser power. Using a value between these two is a compromise between the two limitations. Using a constant fluence, it can be calculated that a 30 μm spot size will require approximately 115 μJ of energy. On the other hand, if the pit diameter is 30 μm and a 676 mm^2 area needs to be covered in a second, it could be done using 30W of laser power, 270kHz frequency and a scanning velocity of 13.5m/s. When the multi-spot optic is used, creating 5 spots the whole surface area of 156x156 mm^2 could be processed with 150W of laser power. Industrial lasers at this power level and providing the required high beam quality are soon to be expected on the market and will allow the pitting process to be fast enough for industrial use. An alternative to the single laser approach is to use multiple low power lasers that already exist.

3. Project Summary

The project objective is to demonstrate the feasibility of laser-based texturing of solar cells for improved efficiency using a technique which is scalable to production. The approach is to develop a high-throughput laser process and to design a concept for a beam manipulation system which meets the requirements set by the laser process and production goals. The project is divided into four main tasks to proof the concept. The respective project plan is shown in Figure 1.

- Laser processing station modification
- Laser process development
- Designing and testing diffractive optics (or other methods of beam splitting)
- Characterizing laser texturing in solar cells.

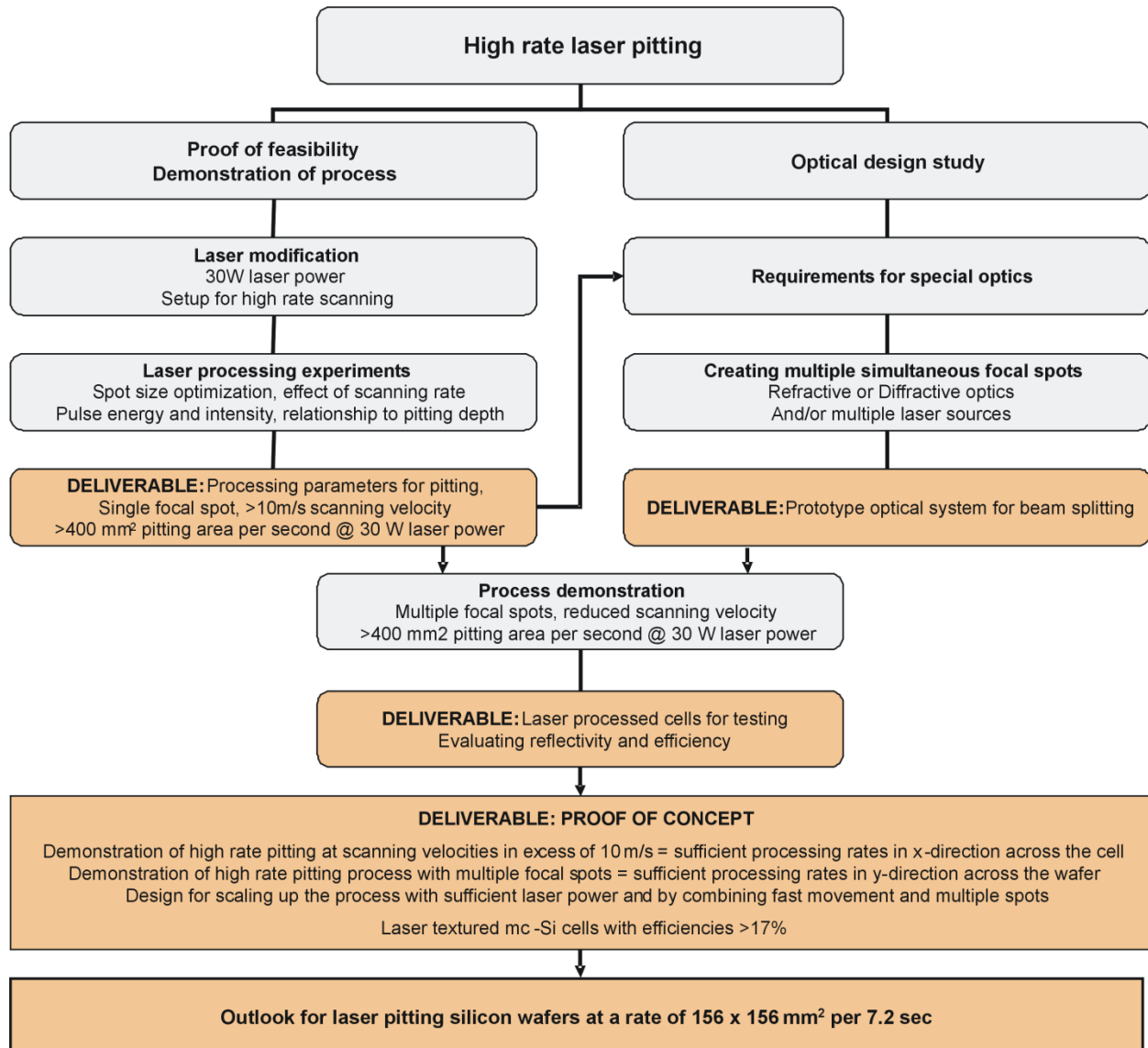


Figure 1: Project Plan

3.1 Laser modification and optical setup

The system is based on a unique MOPA fiber laser and of which first commercial systems became available at the time of the project start (09/2009). Instead of upgrading Fraunhofer's prototype MOPA laser to output power up to 30W, an industrial 25W MOPA laser (Pyrophotonics) was selected for the process development. The processing workstation was upgraded with a water-cooled digital galvanometric scanner (Scanlab) to reach high linear velocities. The scanner was tuned for vector processing and included sensors for self-calibration.

The setup (Figure 2) comprised the laser, mirrors for aligning the beam into the scanner, a polarizer and a $\lambda/2$ plate to adjust the laser power without changing pulse parameters, an variable beam expander, galvanometer scanner (IntelliScan 14) and 80mm focusing lens. The setup also includes a fast photodiode, which was used to verify the real pulse shape and length. In addition, a 163mm focal length optic was used providing a larger spot size.

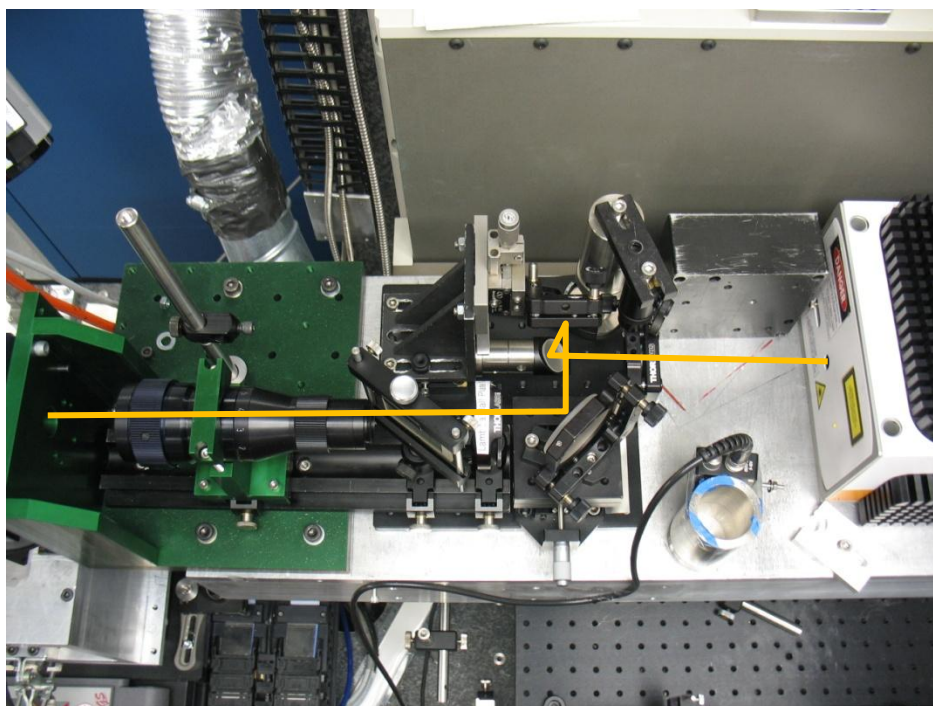


Figure 2: Optical setup and the beam path.

The only challenge in using this setup was that the focal position varied depending on the power set by the polarizer. There also were slight variations in the focal spot diameter. The focal spot was measured with various processing parameters ranging from 20 to 330ns, 62.5 to 125kHz and 3.9 to 20W laser power. The power was always maximized from the laser and then reduced using polarization to create a pulse energy required for the experiments. The beam expander was set to a value of 1x. Focus was always set to the surface, unless otherwise stated. The focal spot size varied slightly with the processing parameters, but the radius was always between 8.4 and 9.1 μ m when the 80mm optic was used.

3.2 Laser process development

The texturing approach is to create a grid of blind holes or pits in the mc-Si wafer surface using a laser and then chemically etching the surface. The objective of the laser process development is to demonstrate a laser-based pitting process which can be scaled to production. The numeric goal of the project is to demonstrate pitting exceeding texturing rate of 400mm² per second using 30W average laser power. Once this rate has been reached using high velocities and a single beam and/or lower velocities and multiple beams, the process can be scaled into production by scaling the laser power accordingly.

Key elements to reaching a very high pitting rate are minimizing the pulse energy and pulse width using a given focal spot diameter. The target depth was 10 μ m. It should be noted that there are several optimal processing schemes, depending on the pit size. A smaller pit diameter reduces the pulse energy requirement and makes it possible to process more pits per second – but the pits cover less area, and vice versa.

The design of experiments (DOE) comprised a broad range of parameter studies to establish optimal settings for laser pitting:

- Effect of pulse width on process efficiency
- Effect of pulse energy on the pit depth
- Effect of scanning velocity on pit depth
- Analyze process sensitivity, velocity and focal tolerance

The main finding in the process development was that the pulse width has the most significant effect on the pit depth. When the pulse energy was increased by a factor of approximately 6 from 42 μ J up to 256 μ J, the reached pit depth increased only 27%. At the same time, if the pulse width was increased by a factor of six from 55ns to 330ns the pit depth increased by over 300%. It is therefore essential to optimize the pulse width for the application to reach highest possible pitting rates. The correlation between the pulse parameters and pit depth is presented in Figure 3.

Pits of depth 10 μ m are required for the application. The least pulse energy capable of creating the desired depth is 50 μ J using a 80mm focusing optic. Considering the average power on the work piece to be 20W, this would give a theoretical pitting rate of 400,000 pits per second and with a pit spacing of 20 μ m (edge to edge) the theoretical speed would be up to 640mm²/s. However using a 80 mm optic, the maximum scanning velocity is 8,000mm/s limiting the pitting rate to 360mm²/s, which is 10% less than the target of 400mm²/s.

An optic with a focal length of 163mm was also tested for pitting. This optic increases the focal spot diameter and the pit size, but allows to move the laser beam at velocities up to 16m/s. The lowest energy for reaching a 10 μ m pit depth using this optic was 195 μ J resulting in a theoretical pitting rate of 100,000 pits per second. Calculating the pitting rate in area from ablated coverage, a rate of 360mm²/s is possible. This value however might be limited by the available laser power. The optimal beam diameter for the pitting process is expected to be between the two tested solutions. Further tests to confirm this will follow.

Sensitivity analysis showed that a change of 20% in the pulse energy typically results only in a less than 4% difference in the pit depth, which can be regarded as negligible. The pulse width has a far greater impact. A 20% change in the pulse width typically causes a 15 to 20% change in the pit depth. However, the pulse width is very well controllable, so this does not noticeably impact the process sensitivity.

Focal tolerance was found to be an important factor in the pitting process. Especially when using a long pulse width and low pulse energy, the process is not tolerant to large changes in the focal position. A ± 0.1 mm change in the focal position resulted in a 2 μ m difference in the pit depth and a shift greater than ± 0.2 mm is capable of reducing the ablation rate close to zero. Using higher pulse energy and shorter pulse width, in other words increasing the intensity of the pulse, the process becomes more tolerant and at 164ns and 86 μ J pulse parameters a ± 0.2 mm change in the focal position causes a less than 2 μ m difference in the pit depth.

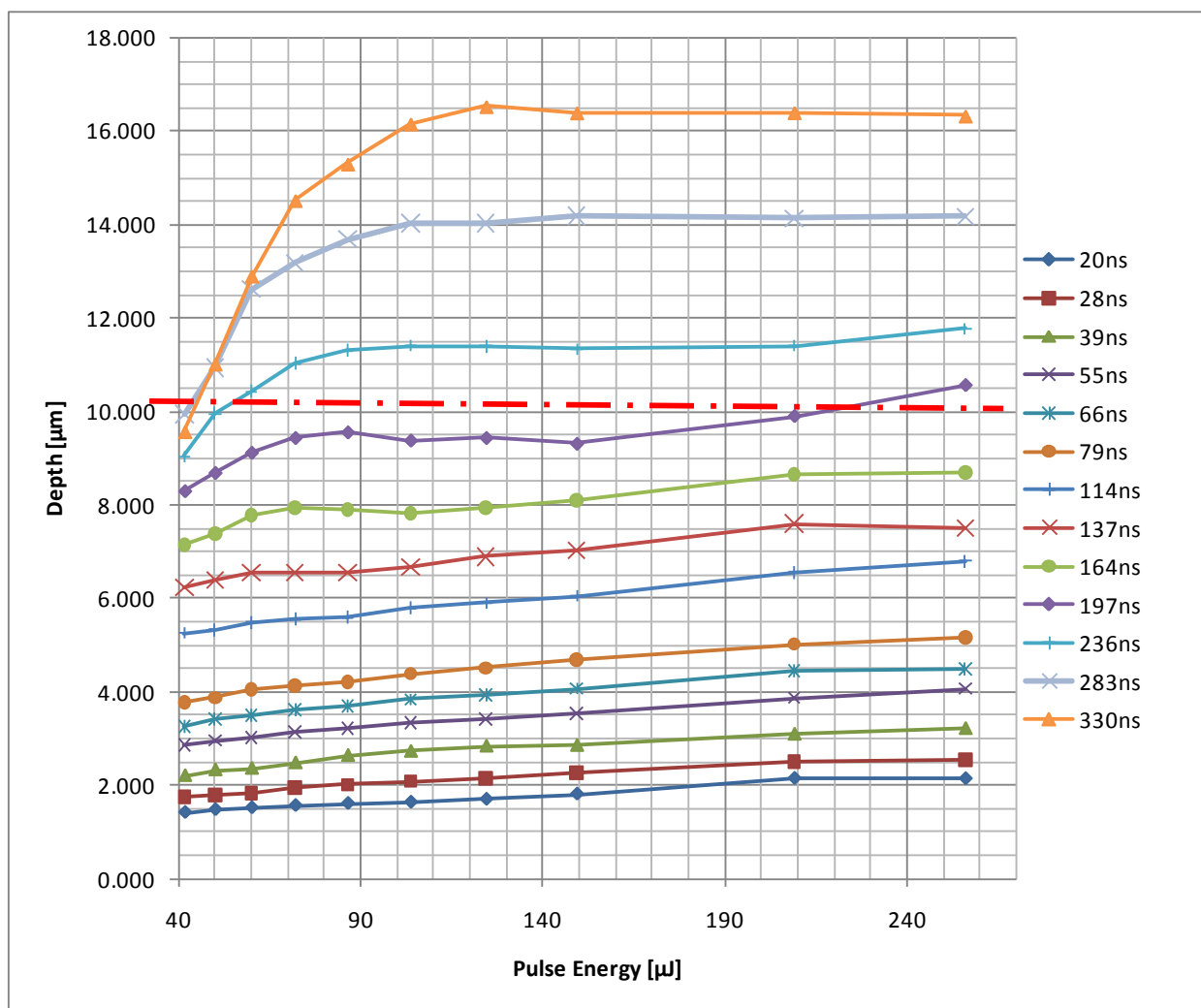


Figure 3. Relationship between processing parameters and pit depth using 80mm focal length optics.

Finding of a suitable measurement technique for accurately determining the pit depth took initial more time than expected and slightly delayed the completion of the process development task. A solution for performing accurate measurements was found using white light interferometry after qualifying different measurement systems.

In summary, the conducted experiments showed well the dependency between the pulse parameters and the pit depths and revealed a lot of data on applicable processing parameters for the pitting operation. With the shorter (80mm) focal length, resulting in a smaller pit diameter it was possible to show a theoretical pitting rate of 400,000 pits per second, which exceeds the goal by approximately 60%. However, at the focal length the maximum scanner velocity is not quite sufficient to achieve the expected area coverage. With the longer 163mm focal length optic, the maximum pitting rate was 100,000 pits per second, with the limit being set by the available laser power. In both cases the pitting rate was 10% below the set goal.

The optimal laser parameters for pitting were with the 80mm optic: 236ns pulse with 72μJ energy. These parameters are fast enough for pitting, allow room for focal tolerance changes in process and create a pit depth of more than 10μm. For 163mm optic the optimal parameters are 195μJ

pulse energy and a pulse width between 346ns and 498ns. An image of a surface sent for further testing is presented in Figure 4.

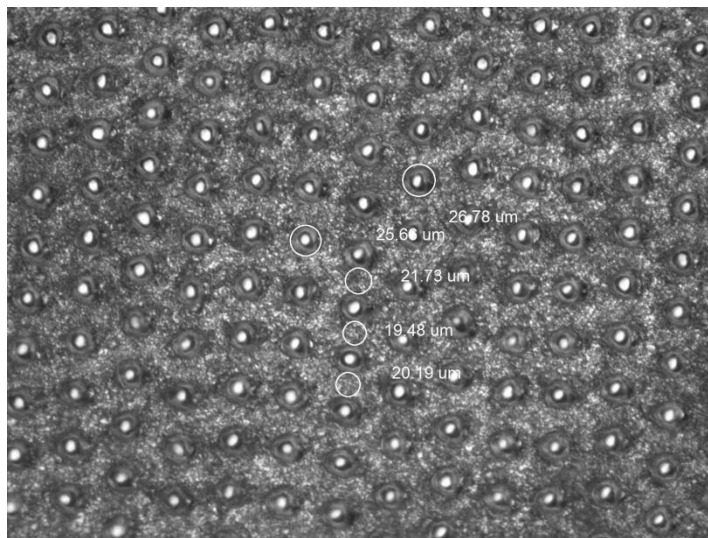


Figure 4. A surface processed with 164ns pulse width, 86μJ pulse energy and 8,000mm/s scanning velocity. Pit diameter: 25μm, pit spacing (center to center): 45μm. Calculated pitting rate without scanner delays: 360mm²/s.

Wafers for reflectivity and cell testing were textured completely using two sets of parameters. A set of wafers were textured using optimized parameters for reaching a texturing depth of >10μm (200kHz, 250ns, 13.0W, 8,000mm/s). The theoretical pitting rate using these parameters was 320mm²/s with the pit distance being 40μm in both directions. In reality the 38.4mm x 38.4mm area took 5.56 seconds to scan, due to the masking technique and scanner acceleration and delays. Due to laser operation, the edges of the textured area were masked to produce a defined uniform textured area without inconsistency in the ends of the scanning lines, created to scanner acceleration and deceleration. A complete cell was textured in 16 areas, sized to fit the scanner field of view. The wafer was positioned on a vacuum fixture, which held the wafer in position and also limited any warping during processing. The vacuum was created using a vacuum pump to suck air through a porous aluminum block below the wafer. Image of the texturing process and the setup is presented in Figure 5.

In order to compare the dependency of the cell efficiency on the aspect ratio of the pits, ten wafers were textured using processing parameters creating pits of depth 16-20μm. This pit depth is close to the pit diameter creating steeper edges and thus theoretically improving absorption and light trapping. Used parameters were: frequency 150kHz, pulse width 400ns, power 20.5W, velocity 6,750mm/s and pulse to pulse spacing 45μm. The theoretical pitting rate was thus 150,000 pits per second and 304mm²/s. Laser processing produced high quality pits at very high rates. A textured wafer is presented in Figure 5.

One concern in laser pitting is the effect of the thermal impact on the top side of the wafer on the warping. Using the processing method presented here, warping was measured to be only 1.1mm at the higher used laser power. Figure 6 presents an image of the wafer after laser processing. Slight upward bending can be seen from the edges.

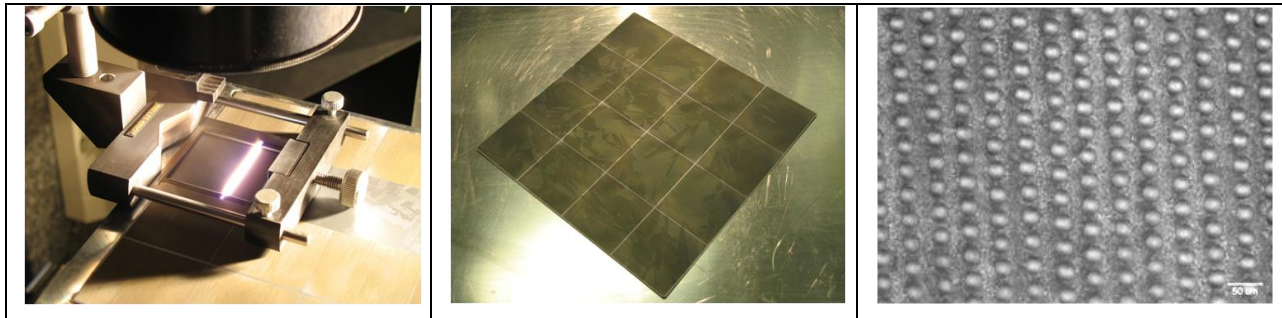


Figure 5: Laser pitting process and texture wafer (pitting rate: 150,000 pits per second)

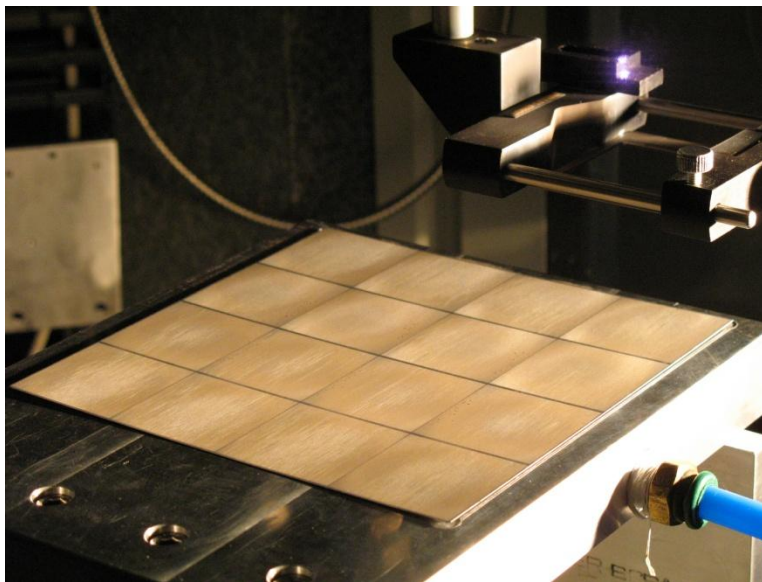


Figure 6: Warping of the cell was approximately 1.1mm after processing. Slight bending is visible from the wafer edges.

3.3 Optical design study

A special optical setup is required that splits the collimated laser output beam into several separate focal spots to meet current production volumes for in-line wafer processing. Optical design studies are being performed to identify and evaluate principle setups for multiple beam splitting. The following parameters were specified for the resulting beam:

Single spot diameter	20μm
Number of spots	6-8
Max. size of beam array (diameter)	14mm
Distance between spots	40μm or multiples of 40μm

Three principle designs were being investigated. The assessment focuses on the optical simulation of the achievable spot sizes and the validation of the design for manufacturability.

A. Splitting the homogenized collimated beam spatially with an array of cylinder lenses

Cylindrical lens arrays consist of spherical cylinder lenses that are etched into a glass plate with constant pitch of approximately 0.5mm. The critical design step is to sufficiently homogenize the collimated beam to ensure the same power for each single spot. The collimated beam is then split into multiple beams in one axis and focused onto the same image plane in the other axis.

B. Splitting the beam with optical elements of variable reflection

The beam is split into multiple separate beams using beam splitters with different reflectivity. The following reflectivity is needed for a 7x beam splitting:

Mirror no.	Reflectivity	Transmitted	Reflected
1	14%	86%	14.3%
2	17%	71%	14.3%
3	20%	57%	14.3%
4	25%	43%	14.3%
5	33%	29%	14.3%
6	50%	14%	14.3%
7	100%	0%	14.3%

Each single beam is reflected with a slightly different angle (7). Focusing the beams with an F-Theta lens realizes spots with at different position. A disadvantage of this approach is that the angle of incidence for each single beam is different.

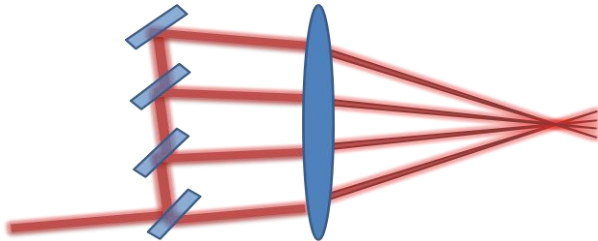


Figure 7: Beam splitting using mirrors with variable reflectivity. Each single beam is reflected with a slightly different angle to realize different spot positions.

C. Splitting the beam using a polarization splitter

The variable beam splitter used in approach 2 can be replaced by a polarization beam splitter and $\lambda/2$ waveplates. The waveplates enable to continuously adjust the reflectivity on the beam splitter, allowing adjustment for equal power in each spot.

Beam splitting with optical elements of variable reflection (option B) was selected for further development. To realize the high accuracy needed for this setup, the approach has been modified. The concept includes two mirrors; a 100% reflecting mirror and a mirror, which reflects different

portions of the beam. When the beam comes in to the system, a part of it will be transmitted (about 1/5 of the total power of the beam) and rest is reflected onto another coating which is optimized to transmit a similar amount of power than the first one. The next coating does the same until the balance is delivered into the scanner. The beam quality stays constant all thorough the optics and the amount of transmitted power of each beam can be controlled by selecting appropriate coatings. The advantage of this setup is that equal spacing between the spots is maintained by the flatness of the mirror. The pitch can be adjusted by changing the angle between the two mirrors.

Figure 8 shows the simulation results of the multi-spot optic providing 5 spots. The beam is nearly diffraction limited. Homogenous power can be maintained using different power levels according to Table 1, option 1.

Option 1				Option 2		
Mirror no.	Transmission	Reflected	Outcoupled	Transmission	Reflected	Outcoupled
1	20%	80%	20.0%	22%	78%	22%
2	25%	60%	20.0%	22%	61%	17%
3	33%	40%	20.0%	38%	38%	23%
4	50%	20%	20.0%	38%	23%	14%
5	100%	0%	20.0%	100%	0%	23%

Table 1: Different options for multi-reflecting mirror. Option 1 uses 4 different coatings for optimal power allocation. Option 2 uses a simplified approach with 2 different coatings.

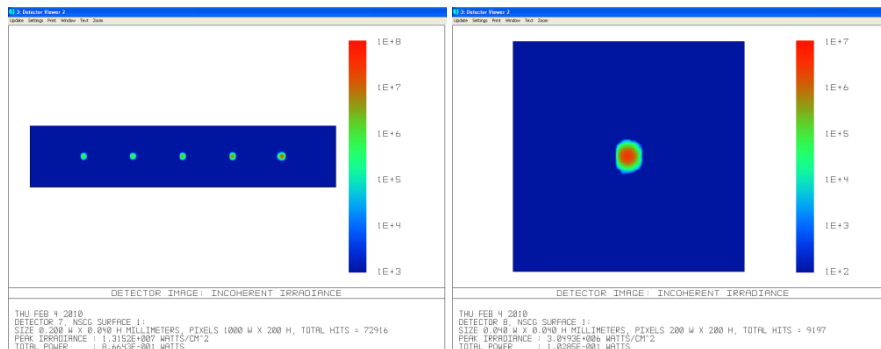


Figure 8: Simulation results for multi-spot optic. The right image shows a single spot with nearly diffraction limited spot geometry.

After completion of the optical design, a manufacturer capable of providing the multi-coating mirror was identified. The long lead time of this component (10 weeks) caused a slight delay of the completion of this task. The final setup for the beam splitting optic is shown in Figure 9.

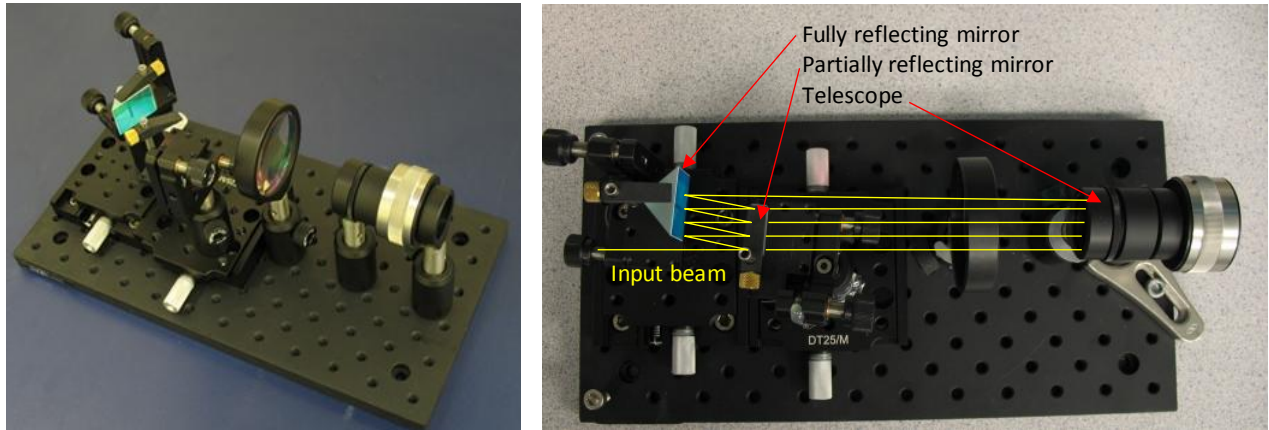


Figure 9: Setup for the multi-beam optic.

The beam characteristics were measured using a Primes Microspot monitor. The beams were measured with the pump current being 27A and the frequency was 100kHz. The results of the measurements are shown in Table 2

Table 2. Beam characteristics. The first beam marked as 1, the last (balance) marked as 5.

beam	power setting [A]	power [W]	focal position z [mm]	beam radius [um]	beam diameter [um]
1	27	1.48	16.26	15.60	31.20
2	27	1.31	16.23	12.72	25.43
3	27	1.45	16.12	12.42	24.83
4	27	1.51	16.19	12.41	24.83
5	27	1.99	16.44	13.81	27.62
Total power:		7.74	Average diameter:		26.8

The power of the individual beams varied from 1.31 W to 1.99 W. The balance beam had the highest power, which also indicates that the variation between the beam powers can be reduced by changing the reflectivity of the coatings. The beam radius varied between 12.4 μm and 15.6 μm , with the first beam being slightly larger than the others. The focal position of all beams was within a small range. The beams were measured individually. The field of view of the Microspot monitor could only accommodate three of the five beams. Beam profile and power measurements are presented in Figure 10.

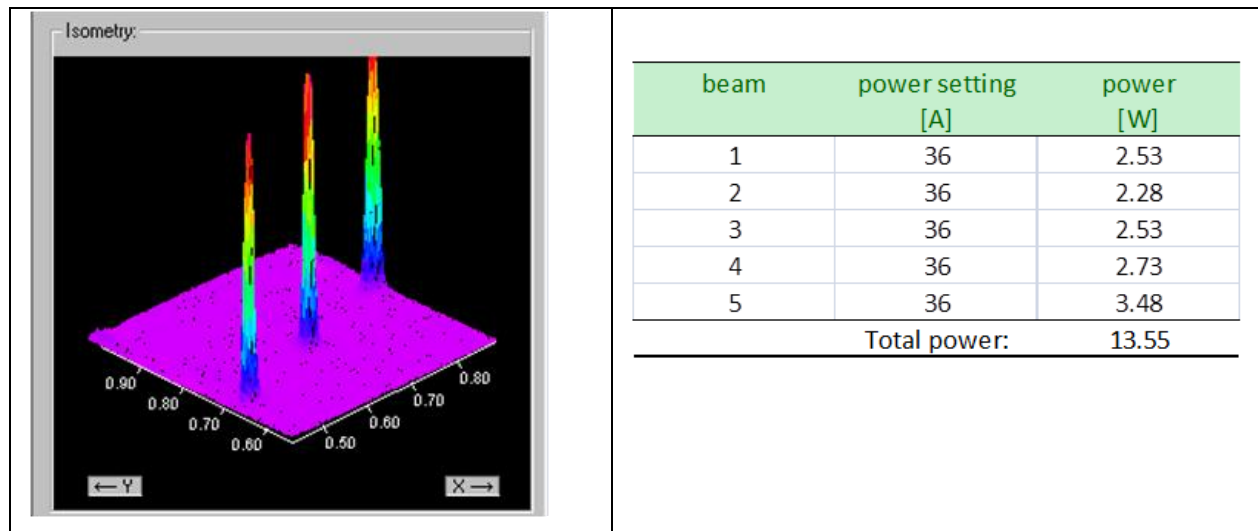


Figure 10: Beam profiles and power measurements of the multi-spot optic.

Power levels of the individual beams were also measured using higher power. The results are shown in Figure 10. Similar results were obtained: power of the last beam was higher than the first four beams. The first beam marked as 1, the last (balance) marked as 5.

Ablations tests on silicon were performed to prove the feasibility of the optic. Sets of lines presented in Figure 11 were processed using 50kHz frequency. The spacing between the lines was 0.24 to 0.25mm, meeting the requirement for producing beams at a spacing of 40µm or multiple of that. However, beam five, which does not pass through the partially reflective optic is spaced at a distance of 0.28mm of beam four. Initial testing of the multi-spot optic has been performed using optimized parameters developed for the single beam processing. The pitting results are as predicted and comparable to what was achieved using the single beam.

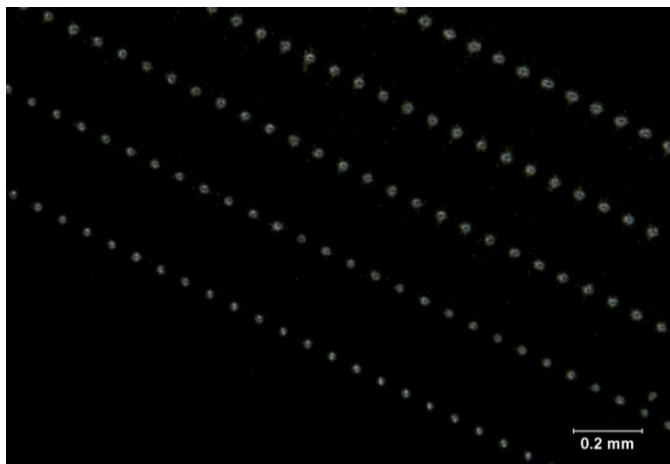


Figure 11: Series of lines of pits processed using the multi-spot optics.

3.4 Characterization of laser textured surfaces

The reflectivity testing of laser textured surfaces was performed by the industrial partner. Standard, state-of-the-art wafer processing and measuring techniques were applied. The textured material underwent an alkaline etch, which is typically used after laser drilling process to clean out the holes, remove any laser damage, and remove the subsurface damage from sawing in the as-received wafers. Here, the objective for etching was to widen and deepen the 10 μ m deep surface pits created by the laser.

The reflectance of wafer material textured with 4 different laser parameter settings was measured and compared to un-textured wafer surfaces. Figure 12 summarizes the results on surface reflectance for the different parameter settings as well as for the un-textured surface ("center" and "backside"). Three samples were measured for each condition. The measurements show surprisingly no distinct difference in reflectance between laser textured and un-textured surfaces over a wide wavelength range reaching from 300nm to 1150nm. The small "jump" in reflectance at 90nm is due the change of the detector.

Further analysis of the sample surfaces reveals a rather smooth surface of the wafer. Figure 13 shows a representative laser-textured wafer surface after etching. The image was taken using a 3D optical profiler microscope, which provides a high depth of focus. The applied etch protocol has turned the laser pits into a rather smooth surface profile with flat bottom features that show a periodicity of approximately 45 μ m. It was concluded that the applied etch was too aggressive and removed most of the created pits instead of enhancing the surface texture and its roughness.

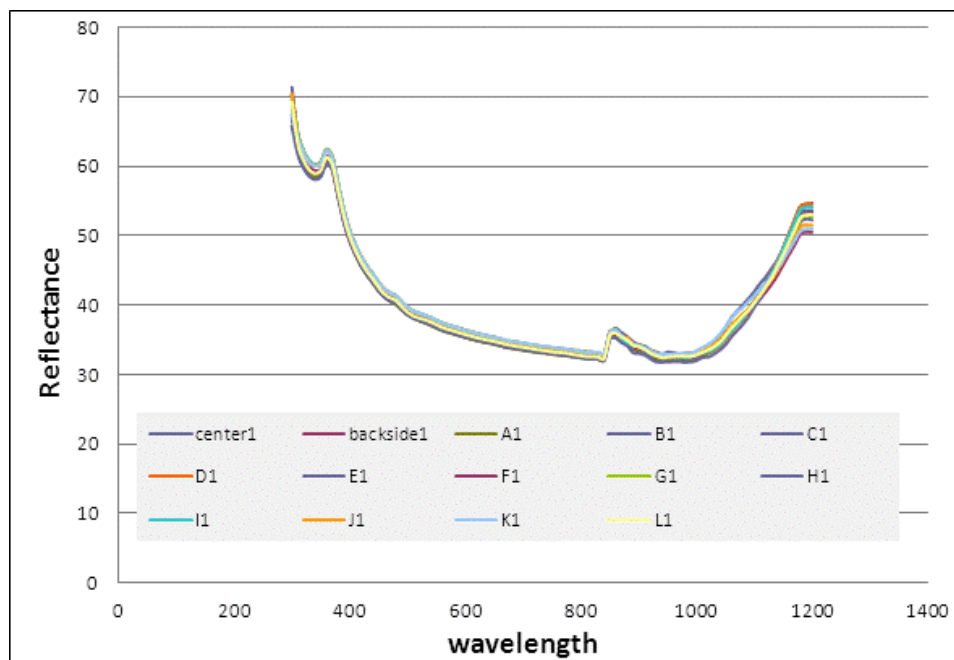


Figure 12: Surface reflectance of laser textured and as-received wafer surfaces

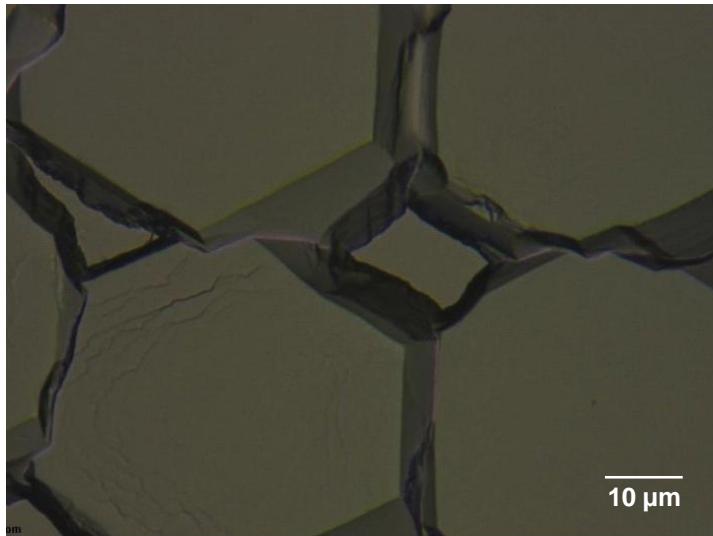


Figure 6: Image of laser-textured surface after etching

Further optimization of the etching process for laser textured wafers is required which goes beyond the scope of this project and is subject of follow-on development at the industrial partner. Additional wafers have been laser textured and will be etched and characterized to better match the laser pitting and the etching process for optimum light trapping conditions.

4. Developed Products and Technology Transfer Activities

The industrial partner on this program was acquired during the course of the development by a leading equipment manufacturer for solar cell manufacturing. The results of this study on high rate laser texturing of silicon wafers were transferred to both parties and are under further evaluation. Additional efforts in on optimizing wafer post processing steps are required to fully utilize the benefit of the laser textured surfaces and to move the technology to process implementation and production validation.

The conducted studies on laser ablation of silicon with flexible pulsed fiber lasers provide an extremely useful database for other applications in solar wafer processing. Based on the knowledge and experience gain in this program, Fraunhofer has developed high-rate drilling processes for solar wafer using Emitter Wrap-Through (EWT) technology. Drilling of 6,800 holes per second in a 190μm thick wafer using less than 20W of laser power is demonstrated, which represents a 300% process efficiency improvement. In addition, Fraunhofer is currently subcontractor to a leading US solar panel manufacturer in a DOE funded F-PACE project, where it utilizes the gained know how on silicon texturing, EWT-drilling and multi-beam optics to develop highly efficient drilling processes for solar wafers using Metal-Wrap-Through (MWT) technology.

Fraunhofer also has posted results on laser processing (texturing, EWT-drilling) for solar applications at www.clt.fraunhofer.com.